ROCK STRIKE TESTING OF TRANSPARENT ARMOR

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GVSS Paper
NLE-01v2

ABSTRACT:

ATPD 2352 is used by the Government to purchase transparent armor for ground combat and tactical vehicles. A Rock Strike requirement is omitted from the present and former revisions of the ATPD. This omission is often cited as a shortcoming of the ATPD. The necessity of such a requirement will be discussed.

While there are multiple sources of rock strikes on these vehicles, it is probably the hazards of hand thrown and tire thrown rocks that predominate. Concomitant damage resulting from detonations of IEDs/EFPs etc. is assumed to be battle damage and is not of concern in this specification.

6 and 12 mm ceramic bearings were fired at speeds ranging from 40 to 150 f/s (12 to 46 m/s or 27 to 102 mph). The bearings were used only once.

Each speed, diameter, and design category was repeated 24 times. The number of iterations was sufficient to have some confidence in the repeatability of the tests.

Two test target design categories were used. One design had a glass face and one had a crystalline glass face. The interlayer adhesive was consistent through both designs and neither had a “spall liner.” The glass design had lateral dimensions of 6 x 6 inches while the crystalline glass faced design was 4 x 4 inches. The smaller was chosen to reduce the cost of the coupons and to provide instant identification of the two designs. Neither recipe Is a currently supplied armor to prevent problems with proprietary cross-talk.

Expected results included lower speed damage thresholds, depth of damage variations, delamination variations, statistical variations of damage, and energy vs. damage correlations. The results indicate that further work is necessary.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
18 AUG 2010	**N/A**	**-**

4. TITLE AND SUBTITLE
Rock Strike Testing of Transparent Armor

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
David N. Hansen, Ph.D.; Ashley Wagner

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA

8. PERFORMING ORGANIZATION REPORT NUMBER
21029

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)
TACOM/TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
21029

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at 20th U.S. Army Ground Vehicle Survivability Symposium, U.S. Army Tank-Automotive and Armaments Command Research, Development, and Engineering Center, (TARDEC), Warren, MI, USA, 18-19 August 2010, The original document contains color images.

14. ABSTRACT
ATPD 2352 is used by the Government to purchase transparent armor for ground combat and tactical vehicles. A Rock Strike requirement is omitted from the present and former revisions of the ATPD. This omission is often cited as a shortcoming of the ATPD. The necessity of such a requirement will be discussed. While there are multiple sources of rock strikes on these vehicles, it is probably the hazards of hand thrown and tire thrown rocks that predominate. Concomitant damage resulting from detonations of IEDs/EFPs etc. is assumed to be battle damage and is not of concern in this specification. 6 and 12 mm ceramic bearings were fired at speeds ranging from 40 to 150 f/s (12 to 46 m/s or 27 to 102 mph). The bearings were used only once. Each speed, diameter, and design category was repeated 24 times. The number of iterations was sufficient to have some confidence in the repeatability of the tests. Two test target design categories were used. One design had a glass face and one had a crystalline glass face. The interlayer adhesive was consistent through both designs and neither had a spall liner. The glass design had lateral dimensions of 6 x 6 inches while the crystalline glass faced design was 4 x 4 inches. The smaller was chosen to reduce the cost of the coupons and to provide instant identification of the two designs. Neither recipe Is a currently supplied armor to prevent problems with proprietary cross-talk. Expected results included lower speed damage thresholds, depth of damage variations, delamination variations, statistical variations of damage, and energy vs. damage correlations. The results indicate that further work is necessary.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

BACKGROUND

ATPD 2352 is in its R revision. Many of the changes are the product of input from vendors as well as PMs. There are several concerns with the ATPD. Lisa Franks demonstrated that a large part of the cost of Transparent Armor, TA, was replacements necessitated by damage due to rock strikes.[1] The largest part, about 63%, of the costs-of-replacement was due to combat damage while rock strike contributed about 32%. While little can be done to eliminate combat damage, rock strike damage avoidance would seem to offer a fruitful area for costs elimination.

Other areas of costs reduction were indicated by the Franks' report. Namely, costs could be significantly impacted by the elimination of clouding due to delamination. This will be addressed in other research studies. A small part of this study was dedicated to delamination.

6 and 12 mm ceramic bearings were fired at speeds ranging from 40 to 150 f/s (12 to 46 m/s or 27 to 102 mph). The bearings were used only once. The number of iterations was sufficient to have sufficient confidence in the repeatability of the tests. Following strikes by the silicon nitride bearings, the samples were thermally cycled to see if the thermal expansion and contraction would contribute to the glass-glass interface delamination.

In a full-up transparent armor there is usually a spall liner on the inside or "crew" surface. The spall liner catches the fragmenting armor but has the nasty attribute of having a large coefficient of thermal expansion. This thermal expansion would be a significant driver in creating delamination at the rear of the design stack. This test limited its study to delamination due to thermal shocking of the impacted coupon glass layers and possible crack extensions at damaged locations. The lack of there being a "spall liner" makes this part of the test less than definitive.

Delamination and Rock-Strike definitions in ATPD 2352 are lacking with the exception that delamination in the parts as supplied is not allowed. Quality assurance staffs within PMs have privately reported problems with delamination, and the staffs have indicated that this is a significant problem. Delamination is certainly the next most fruitful area for improvement and will be studied shortly. Based on current data, rock strike amelioration has more cost savings potential and so is more urgent.

This report concerns laboratory tests using 2 diameters of ceramic ball bearings fired at speeds ranging from 40 to 150 f/s (25-100 mph). The tests were highly repetitive with 24 coupons being tested at each 10 f/s increment of speed and at each diameter. The vendor was allowed some selection latitudes. The vendor chose the actual ceramic bearing material; it had to be from one source and one lot for both diameters. The diameters were allowed to be what was commercially available but near ½" and ¼" in diameter. The size was chosen based on the assumption that the larger the rock the less frequently the rock would be encountered. Larger hand-thrown rocks would be encountered but were not part of this test. This larger class of rock size may be better evaluated with a drop tower test.

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[1] Briefing by: Lisa Prokurat Franks, US Army Tank Automotive Research Development and Engineering Center, and David Holm and Raymond Kleinberg, TACOM LCMC Cost & Systems Analysis Directorate; "Transparent Materials for Armor – A Cost Study"

The transparent armor samples (coupons) were either 6” squares or 4” squares. The 6” squares were an “all glass” recipe while the 4” squares were a “glass with crystalline glass strike face” recipe. All interlayers (adhesive layers) were the same specification. The specification was for Huntsman PE 399 urethane.

The 6x6 recipe that was suggested is shown below with layer 1 being the strike face.

Table I. Recipe for 6 x 6 in. sq. All Glass Coupons

1	0.236”	Annealed water white (low iron) clear glass
2	0.025”	Urethane Interlayer Huntsman PE 399
3	0.388”	Annealed water white clear glass
4	0.025”	Urethane Interlayer Huntsman PE 399
5	0.388”	Annealed water white clear glass
6	0.025”	Urethane Interlayer Huntsman PE 399
7	0.490”	Annealed water white clear glass

The 4x4 recipe is shown below with layer 1 being the strike face.

Table II. Recipe for 4 x 4 in. sq. Glass Ceramic Faced Coupons

1	0.388”	Glass ceramic
2	0.025”	Urethane Interlayer Huntsman PE 399
3	0.388”	Annealed water white clear glass
4	0.025”	Urethane Interlayer Huntsman PE 399
5	0.388”	Annealed water white clear glass
6	0.025”	Urethane Interlayer Huntsman PE 399
7	0.388”	Annealed water white clear glass

The vendor was allowed to use commercially available thicknesses. The thicknesses specified by the vendor are given below:

Table III. Vendor Modified 6 x 6 Recipe

Size	Layer	Material	Thickness			PSF
			Suggested (inch)	Vendor (inch)	Vendor (mm)	
6 x 6	1	Glass	0.236	0.250	6.0	3.20
"	2	PE 399	0.025	0.025	0.6	0.14
"	3	Glass	0.388	0.375	10.0	5.33
"	4	PE 399	0.025	0.025	0.6	0.14
"	5	Glass	0.388	0.375	10.0	5.33
"	6	PE 399	0.025	0.025	0.6	0.14
"	7	Glass	0.490	0.500	12.0	6.40
		Totals =	1.577	1.575	39.8	20.68

Table IV. Vendor Modified 4 x 4 Recipe

Size	Layer	Material	Thickness			PSF
			Suggested (inch)	Vendor (inch)	Vendor (mm)	
4 x 4	1	Glass Ceramic	0.388	0.388	9.8	5.54
"	2	PE 399	0.025	0.025	0.6	0.14
"	3	Glass	0.388	0.375	10.0	5.33
"	4	PE 399	0.025	0.025	0.6	0.14
"	5	Glass	0.388	0.375	10.0	5.33
"	6	PE 399	0.025	0.025	0.6	0.14
"	7	Glass	0.388	0.375	10.0	5.33
		Totals =	1.627	1.588	41.6	21.95

The water white glass was either PPG Starphire or Pilkington OptiWhite and the adhesive was Huntsman PE 399. The glass ceramic by Corning was not represented to the Government as being any better or any worse than any other glass ceramic but it can be assumed that the product was of good quality as would also be expected of other similar products.

The Government did not specify the material of the ceramic ball bearings. The testing company chose to use silicon nitride; Si_3N_4 not only has a high strength but also has an unusually high fracture toughness for a ceramic[2]. Also, silicon nitride was available as both 6 and 12mm diameter ball bearings with very tight tolerances on their diameter and sphericity. The density of ball bearing grade silicon nitride is expected to be well controlled but was not part of the ball

[2] Wikipedia, Silicon Nitride, http://en.wikipedia.org/wiki/Silicon_nitride.

bearing specification. The contract specified that both be of a single lot and was best met by the silicon nitride products that are of high quality and consistency. The contract also specified that the testing be done with an air-gun launched system with the ball speed being measured for each launch. The contractor met this requirement by creating a system using a speed-gun to measure the speed, a paintball gun, and specially machined barrels. The barrels were precision bored to the 6 and 12mm diameter such that no obturation of the projectiles was required. Precision speed control was obtained by drilling and threading holes transverse to the length of the barrel. Set screws were used to plug the holes which were vented as required to meet the speed requirements of the specified velocity increments.

The contractor was very successful in controlling the average speed. The average for each group of 24 coupons are given below:

Table V. Actual Average Speeds for the Four Design Categories (Averaged over 24 Coupons)

Speed Group	Annealed Glass 6mm ball Average Speed	Annealed Glass 12mm ball Average Speed	Glass Ceramic 6mm ball Average Speed	Glass Ceramic 12mm ball Average Speed
40	42.8	44.7	41.0	44.7
50	48.4	53.9	47.7	53.5
60	61.8	62.4	61.8	61.7
70	71.2	69.0	71.1	69.5
80	84.5	78.3	81.7	78.3
90	88.8	91.8	88.7	90.5
100	99.8	98.9	99.3	100.7
110	110.7	113.4	110.9	107.8
120	122.6	120.0	122.0	123.1
130	131.2	132.5	131.5	128.6
140	142.7	140.5	143.1	139.3
150	151.3	152.8	150.2	153.8

The deviation from the desired average can be found by subtracting the Speed Group value from the Average Speed or by looking at the following table. Note that the five largest deviations are highlighted.

Table VI. Deviation of Average Speed from Speed Group Goal

Speed Group	Ann. Gl. Deviation 6mm	Ann. Gl. Deviation 12mm	Gl. Ceram Deviation 6mm	Gl. Ceram Deviation 12mm
40	2.8	4.7	1.0	4.7
50	-1.6	3.9	-2.3	3.5
60	1.8	2.4	1.8	1.7
70	1.2	-1.0	1.1	-0.5
80	4.5	-1.7	1.7	-1.7
90	-1.2	1.8	-1.3	0.5
100	-0.2	-1.1	-0.7	0.7
110	0.7	3.4	0.9	-2.2
120	2.6	0.0	2.0	3.1
130	1.2	2.5	1.5	-1.4
140	2.7	0.5	3.1	-0.7
150	1.3	2.8	0.2	3.8

This information can be combined with the standard deviations to get an idea of how precise the vendor can control the round to round speed variations. The standard deviations are for 24 repetitions of the test. The standard deviations are given below.

Table VII. Standard Deviation of Each Speed Group

Speed Group	Annealed Glass 6mm ball Speed Std. Dev	Annealed Glass 12mm ball Speed Std. Dev	Glass Ceramic 6mm ball Speed Std. Dev	Glass Ceramic 12mm ball Speed Std. Dev
40	1.4	0.5	2.5	0.5
50	1.5	1.7	1.1	0.5
60	0.9	1.8	0.9	1.3
70	1.1	1.8	1.0	1.8
80	0.7	1.2	3.2	1.1
90	2.5	2.6	1.3	3.0
100	1.4	2.0	1.8	2.8
110	1.9	1.1	1.6	1.7
120	1.3	2.5	1.3	1.5
130	1.6	2.4	1.2	1.3
140	2.4	3.3	1.8	2.8
150	2.0	1.9	2.1	1.3

Note that the deviations are very limited. This is thought to be a product of their means of regulating the speed. That is, they fixed the trigger response and changed the bleed air by opening the transversely drilled holes to achieve the speed stability. The speed stability was

much better than was requested by the contract. Per the contract, the test could be counted if the resultant speed was the goal speed (increments of 10 starting at 40 f/s and ending at 150 f/s) ±6 f/s. All of the speeds were within specification. The actual speed is available for each of the coupons tested, but the goal speed will be used to categorize the data.

Every one of the 1152 coupons were photographed after impact and again after thermal shocking. The photographs were examined and ranked using the table presented below

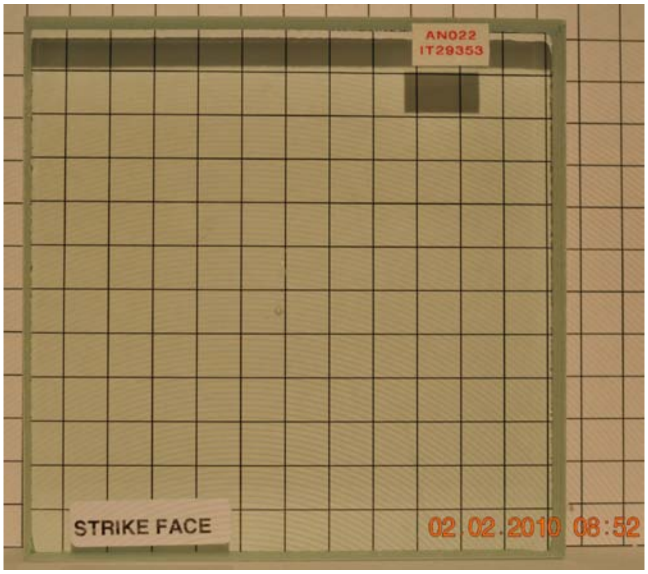
Table VIII. Ranking Catagories

Description of Damage and Rank			Attributes
None	No Shadow	0	Neither shadow nor crack visible
Light Crush	CRS	1	Usually only seen as a shadow.
Small Circular Crack	SCC	2	About half the size of a half inch (grid) square (.25 in.)
Circular Crack	NCC	3	Greater than about .75 and less than 2.5 grid squares
Large Circular Crack	LCC	4	Greater than about two-half inch grid squares
Large Circular Crack with Radial Cracks	LCR	5	Radial cracks not much larger than largest circular crack.
Circular, Radial, Crush, Failures	LCRC	6	Numerous radial cracks not much larger than about 150% of largest circular crack and crush apparent.
Radial Cracks to Edge	RCE	7	Three radial cracks extending 2 or more inches or to the edge of the coupon.

Initially the ranking was very simple. The damage was complex (or large) or simple (and small). This rapidly became insignificant and was discarded in favor of Table 8. Table 8 was expected to give a trend line if the definitions were roughly consistent.

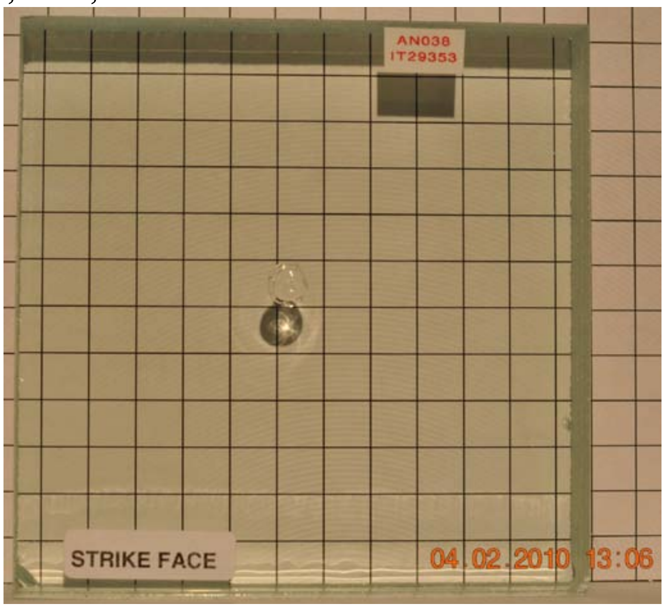
The trend would have to be supportable using simple averages because the fracture proved to be stochastic. At higher velocities damage could range from almost none to large complex fractures with radiating cracks terminating at the coupon edges. As the velocity or speed increased the trend would be toward more frequently occurring large, complex cracks.

The variability of the fracture response is probably best shown by the annealed glass coupons at 130 (132.5 actual average) fps.



Photograph 1. Minimal Damage at 135 f/s, Ranked 1.

There is only a shadow of a small crush in this photo. Actual speed was 135 fps.
130-AN038 is ranked 3, NCC; and is shown below:



Photograph 2. Minor Damage at 129 f/s.

Note that the chip is decidedly larger despite the actual speed being 129 fps.
In the next specimen the recorded speed is the same 129 fps. Notice however that the damage is greater. Not only is there a significant amount of crush, but there is also a group of radial cracks.
130-AN045 is ranked 5, LCR; and is shown below:

Photograph 3. Heavy but not Major Damage at 129 f/s.

As the average damage becomes larger, the spread in the data increase but this is not a good statistical variation. That is, because this is a ranking, and because the ranking is 0 to 7, the possible variability is probably largest near the middle of the ranking.

THERMAL STRESS AND DELAMINATION

Following the impact of the ceramic balls, all of the coupons were exposed to thermal shocking per ATPD 2352. This was done to see if the impact of the spheres sensitized the coupons to delamination or would cause extension of radial cracks.
The delamination was checked with dye penetrant and following a cursory examination of the early data, dye penetrant was reduced to sampling based on the vendor’s experience that no delamination occurred following an impact. In no case was a delamination noticed.
The extension of radial cracks was also followed and is presented in the following plot. Note that there were no crack extensions in the 6mm impacted coupons. Photographs 4a and 4b respectively present a before and an after thermal-shocking visualization.

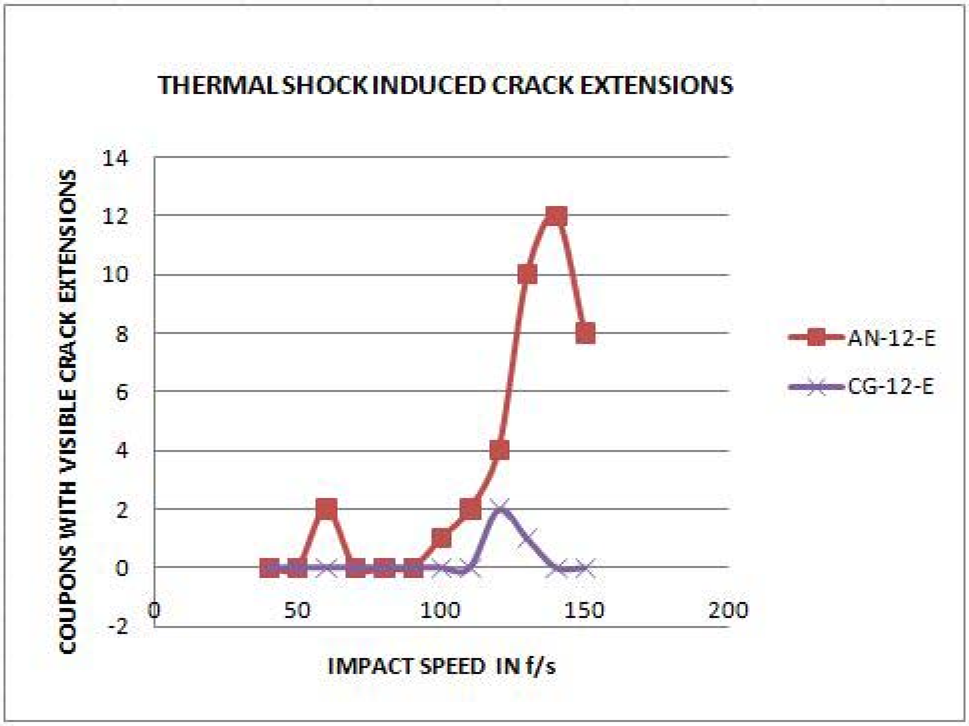


Figure 1. Number of coupons with significant changes in ranking.

Photographs 4a (before) and 4b (after).

Before

After

Note how much the cracks at 1:00 and 8:00 have extended as a result of thermal shocking.

VISUAL RANKING OF THE PHOTOGRAPHS

All photographs of the coupons were ranked using Table 8 without regard to striking ball diameter or speed of collision. It was done for the two groups all-glass (AN for annealed glass) and crystalline glass (CG) strike faces and before and after thermal shocking. The photographs for before and after thermal shocking were stored by their coupon number in separate files. Only after all photographs were ranked were the rankings grouped by speed, ball diameter, and ordered by coupon number. Then the rankings were imported using the photograph number. Since only a few of the 1,152 coupons exhibited crack ranking extensions, the number of extensions was simply counted for the mentioned groupings.

In Figure 2 the average rankings are presented. Note that the 12mm and 6mm results grouped despite the different lateral sizes of the AN and CG coupons. Also note that the 12mm results generate the largest cracks and that the 6mm cracks bottom out at 60 to 80 f/s. The fact that the ranking categories are not linear in terms of damage energy may be contributing to the non-zero values for the bottomed out 6mm values.

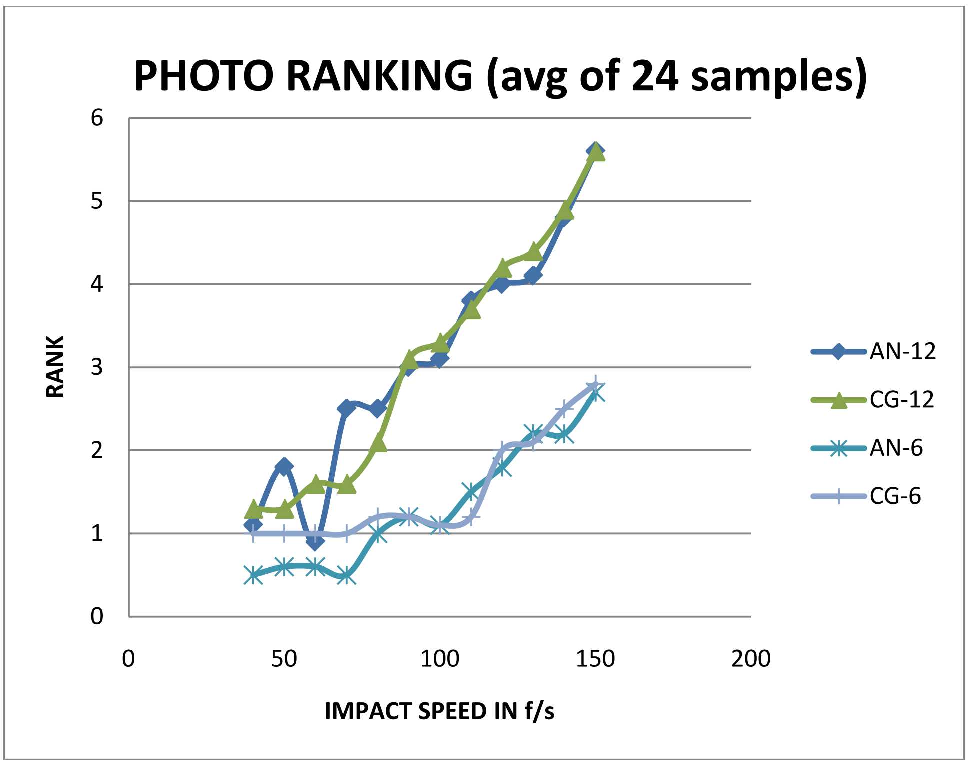


Figure 2. Results of Ranking of Coupon Photographs.

In the contractor report for W56HZV-09-C-L553, the low end damage was assessed as shown below:

Table IX. Number of coupons NOT damaged (24 coupons per group).

SPEED	40	50	60	70	80	90	100	110	120	130	140	150
AN-6	6	4	6	3	-	-	-	-	-	-	-	-
AN-12	7	-	12	1	-	-	-	-	-	-	-	-
CG-6	-	-	-	-	-	-	-	-	-	-	-	-
CG-12	-	-	-	-	-	-	-	-	-	-	-	-

Dashes indicate that all 24 coupons in the group were damaged. This is different from Figure 2 in that Figure 2 is an average of an assessment where this table is a numbering of exceptions. Also, this table indicates that AN-12 had more exceptions than CG-6 contrary to the indication of Figure 2.

ENERGY DISCUSSION

Energy of the 6mm ball at 150 f/s is about 0.4 Joule. For the 12mm ball at 150 f/s it is about 3.0 Joules. The contractor noted that the French gravel test using a deformable aluminum slug impacts with about 200 Joules. This is done with the impact Δ_{time} being relatively long and the velocity being relatively low. Silicon nitride balls probably deliver their impact over a very small Δ_{time} resulting in an impact. Thus, impulse becomes the driving interaction. And, the fact that the balls do not always impart the same amount of damage is probably more realistic than the deformable aluminum slug.

The 12mm silicon nitride ball at 100 mph simulates more closely a rock (brittle) impact that results when two vehicles, each going 50 mph, approach each other. Thus, high speed and brittle behavior are expected.

SUMMARY

Visual examination of after event photographs can yield expected behavior plots that could be inserted in ATPD 2352 to further define the Transparent Armor Specification. Simplification of this plot to a point test at fixed velocity and ball material and coupon size would reduce the cost of such testing. The necessity of doing this test can still be discussed.
One such test could evaluate the expected size and nature of the impact crater while another one at higher velocity could predict the propensity of the crack to extend. This second, higher velocity test is not recommended because all flaws will eventually lead to crack extension. So, a test at about 100 f/s with 10 coupons impacted by 12mm silicon nitride balls may be a good

starting point for rock strike certification. The expected average result should be about rank 3 or about 1.25” circular crack (avg.).

The expected lower velocity crack threshold could not be confirmed. It may exist for the 6mm ball below about 70 f/s but would require different ranking criteria.

Delamination was not demonstrated as a result of impact at this energy level. This type of testing is not recommended to be included in any delamination study.

Variation in response as a function of impact speed was not determined but may be available with further analysis of the data of this test series. A simple sigma may be determined from these data but it must be remembered that this is a variation of a subjective ranking by an individual. Thus, more analysis of these data should be attempted.

Lighting nuances may have induced some of the minor differences between this study and the contractor’s report.